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Quantitative Analysis of the Effect of Optical Probe Positioning on the Measurements of Flattened Diameter of Ocular Cornea for Applanation Tonometry

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Abstract

The precise positioning of optical probe is an attractive technique in application to an accurate assessment of intraocular pressure (IOP) during applanation tonometry. Based on a mathematical model, the influence of the optical probe positioning on the measurements of the flattened diameter of the ocular cornea is analyzed. The measurements of the flattened diameter are evaluated for two cases. One is that the flattened circle's center is concentric with the corneal apex, located in the visual axis of the eyeball, and the other is that the flattened circle's center is offset from the corneal apex. Experimental results show that the present optical probe is position sensitive and only for case one the measured diameter has good agreement with the real diameter. The research results are very valuable for the improvement of an applanation tonometer.

Keywords: Optical probe, intraocular pressure, tonometry, tonometer, flattened diameter measurement

1. Introduction

Determination of intraocular pressure (IOP) is essential to a diagnosis, monitoring or management of glaucoma [1-3]. IOP may be measured by a variety of methods, such as palpation, manometry and tonometry. In the clinical practice, the one most frequently used is tonometry, such as indentation tonometry, applanation tonometry, non-contact tonometry, and so on [4-8].

The measuring technology of the flatten diameter or area of the ocular cornea is mainly used in applanation tonometry. The Goldmann applanation tonometer (GAT) uses a plastic cylindrical probe to

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flatten the corneal surface. IOP is measured by the force required to flatten a predetermined area, exactly 3.06 mm in diameter. Currently, GAT, a fixed-area tonometer, is considered to be the gold standard for clinical use. Similar to the probe of GAT, another has been applied to a hand-held, applanation tonometer introduced by Perkins [9]. Since the patient's accidental eye movement and tremor are ineluctable in applanation tonometry, the precise positioning of the optical probe is a key technique to the accurate determination of the flattened diameter or area of the ocular cornea. These applanation tonometers can effectively measure the IOP, but then new trends reveal that the IOP should be checked with regularity and relatively often to achieve a better reliable diagnosis and management by the clinician and to facilitate the self-operation of a tonometer by patients at home [10]. However, due to the difficulty in operating the GAT, or the high prices of Perkins hand-held applanation tonometer, such tonometers can only be employed by ophthalmologists in hospitals. Recently, a new version of applanation tonometer, with a low-cost and easy-to-use characteristic, has been presented [11]. There is a clear need of a better method for use in the quantitative analysis of the influence of the positioning of the optical probe on the measurements of the flattened diameter of the ocular cornea which in turn would lead toward a better assessment of tonometry.

In this paper, the fabricated optical probe is briefly introduced. Based on a simple mathematical model, the influence of the testing position of the optical probe on the measurements of the flattened diameter of the ocular cornea is evaluated.

2. Optical probe characterization

2.1. Probe optical configuration

The optical probe configuration that is used for measuring the flattened diameter of ocular cornea is shown in Fig. 1. A light emitting diode (LED) is placed at the focal plane of the converging lens. The light emerging parallel from the lens passes through a beam splitter cube. An optical baffle obstructs the light beam that arrives on the bottom surface directly from the top surface of the cone prism. Other beam enters the cone prism is totally reflected at the inclined flank and delivered to the bottom surface. On this surface, it is reflected and then arrives at the opposite inclined flank on the top of the cone prism. The reflected beam, returning from the cone prism, again passes through the beam splitter cube and is imaged onto a photodetector by utilizing a cylindrical lens. In this optical probe, the cone prism also acts as the measurement body touching the ocular cornea to shape the area to be measured in the applanation tonometry [12]. So, the bottom surface of the cone prism is called the applanation surface.

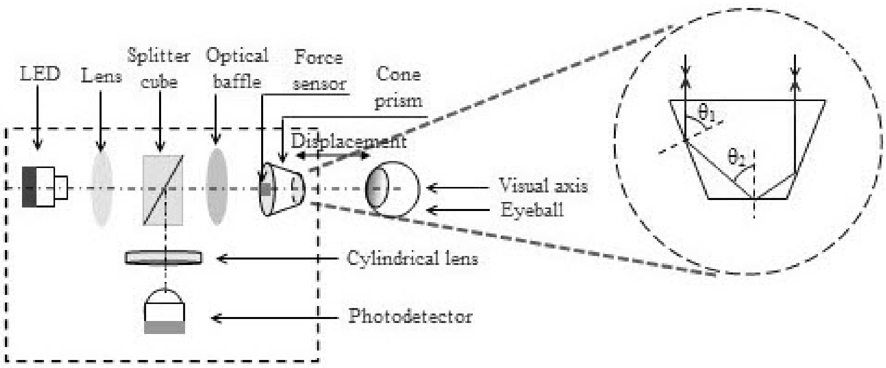

Fig. 1. Scheme of the optical probe characterization

2.2. Measurement principle

When a beam of parallel rays enters the cone prism, it is totally reflected at the inclined flank and then is again totally reflected on the bottom surface, as shown in the inset in Fig. 1. The luminous flux received through the photodetector equals the total luminous flux entering the cone prism. However, when the cone prism is in contact with the eyeball, on the flattened portion of the cornea, there is no reflection or only a weak one because an important part of the light enters the eyeball. Thus, the received luminous flux through the photodetector decreases. Suppose that the medium absorption is not considered, the diminished quantity of the luminous flux can be expressed as

$$\Delta\varphi = R_t k_1 r = \frac{R_t k_1}{2} d \qquad (1)$$

where R_t is the refraction coefficient of the cone prism versus the cornea, r and d are the flattened radius and diameter of the flattened circle of the ocular cornea, respectively; the constant $k_1 = 2\pi D_2 I_0 \cos\theta_2 (1+\cos\theta_2)$, where D_2 is the diameter of the bottom surface of the cone prism, I_0 is the intensity of incident light, θ_2 is the taper of the cone prism and $\theta_1 = 180^o - 2\theta_2$.

From Eq. (1), we know the diminished luminous flux is proportional to the flattened diameter of the ocular cornea. Therefore, after calibrated properly, the output electrical current signal of the photodetector may serve to give the size of the flattened diameter during applanation tonometry.

3. Theoretical analysis

For analyzing the influence of the testing position of the optical probe on the measurements of the flattened diameter of the ocular cornea, a simple mathematical model is constructed, which assumes that the whole eyeball can be approximately modeled as an ellipsoid of revolution and the cornea as a spherical cap. In Fig. 2, the luminous flux on a circle with radius r of the applanation surface in $\boldsymbol{e_1}$ direction can be written as,

$$\varphi(r) = 2\pi D_2 I_0 \cos\theta_2 (1+\cos\theta_2) r = k_1 r \qquad (2)$$

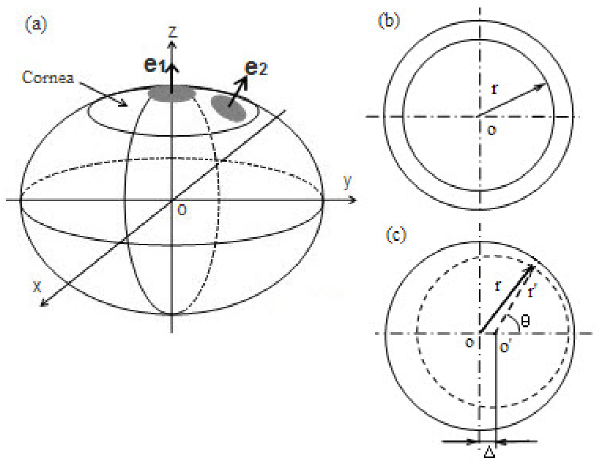

Fig.2. Schematic of flattened circle position corresponding to optical probe placement. (a) mathematical model; (b) $\boldsymbol{e_1}$ direction; (c) $\boldsymbol{e_2}$ direction

Due to the circular symmetry of the light intensity distribution on the applanation circle, the luminous flux on the flattened circle in $\boldsymbol{e_2}$ direction can be deduced as

$$\varphi'(r) = k_2 \int_0^r \int_0^{2\pi} \frac{1}{\sqrt{r'^2 + \Delta^2 + 2r'\Delta\cos\theta}} r' dr' d\theta \tag{3}$$

where Δ denotes the offset value, as shown in Fig. 2(c), and the constant $k_2 = D_2 I_0 \cos\theta_2 (1 + \cos\theta_2)$.

Using Eqs. (1) and (3), we can therefore obtain the flattened diameter of the flattened circle, that is,

$$d' = 2r' = \frac{1}{\pi} \int_0^r \int_0^{2\pi} \frac{1}{\sqrt{r'^2 + \Delta^2 + 2r'\Delta\cos\theta}} r' dr' d\theta \tag{4}$$

According to Eq. (4), the effect of the testing position of the optical probe on the measurements of the flattened diameter of the ocular cornea is evaluated in this study.

4. Numerical results

For the simulation, the parameters of the offset value and real radius of the flattened circle are selected. The real radii of the flattened circles are set to 0.100 mm, 0.200 mm, 0.400 mm, 0.600 mm and 0.800 mm, respectively. For the same flattened circle, the offset value is ranging from 0 to 1.300 mm with an increment of 0.100 mm. The value is set to zero, denoting that the flattened circle's center is concentric with the corneal apex, and the others denoting the distance that the flattened circle center is offset from the corneal apex. A relative error is defined as,

$$\delta = \frac{D - d}{D} \times 100\% \tag{5}$$

where D and d represent the real flattened and computed diameters for the same flattened circle, respectively. A typical example of the flattened circle with real radius of 0.600 mm is given in Table. 1.

Table 1. The relative errors due to different offset values of Δ when the real diameter of the flattened circle is 1.200 mm

Offset value Δ (mm)	Computed diameter d (mm)	Relative error δ
0.000	1.200	0.000%
0.100	0.87554	27.039%
0.200	0.71222	40.648%
0.300	0.60106	49.912%
0.400	0.51935	56.721%
0.500	0.45665	61.946%
0.600	0.40706	66.078%
0.700	0.36692	69.423%
0.800	0.33382	72.182%
0.900	0.30607	74.494%
1.000	0.28251	76.458%
1.100	0.26226	78.145%
1.200	0.24468	79.61%
1.300	0.22929	80.893%

In Table 1, it can be found that when the offset value is set to zero, the relative error is 0.000%. However, when the cone prism's center is slightly offset from the corneal apex, the computed diameter is much smaller than the real diameter. For example, the offset value is only set to 0.100 mm, the relative error up to 27.039%. The larger the offset value is, the larger the relative error. The similar results are found in the other flattened circles with radii of 0.100 mm, 0.200 mm, 0.400 mm or 0.800 mm. Another phenomenon is also found that, for the flattened circle with the same offset value, the bigger the flattened radius is, the smaller the relative error. The reason could be attributed to the contour of the ellipsoidal eyeball with the flat and steep meridians.

5. Conclusions

In this paper the influence of the optical probe positioning on the measurements of the flattened diameter of the ocular cornea is analyzed in detail. The computed results based on a mathematical model demonstrate that the optical probe is position sensitive. Compared with the concentric measurement, the eccentric measurement can induce larger relative error. Only when the cone prism's center is concentric with the corneal apex, the measured diameter has good agreement with the real diameter. The research results are very valuable for the improvement of the applanation tonometer previously presented.

Acknowledgements

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